

days, I have not been able to find any very striking differences between the weather of the two halves of the month.

There was greater cyclonic activity during the second half than in the first, the weather was more changeable, and there was a pronounced southward and eastward

flow of polar air on the 26th-28th. On the whole, the differences were not important. The temperature and precipitation were both rather close to the normal, so close that we feel justified in characterizing it as an average winter month.

HAWAIIAN RAINFALL

By ALFRED J. HENRY

The recent publication by the Weather Bureau of statistics of rainfall and other climatic data for Hawaii¹ puts in convenient form for study the individual monthly amounts of rainfall as recorded for each month of the year at 59 stations in Kauai, 120 in Hawaii, 72 in Maui, and 77 in Oahu, 2 in Lanai, and 5 in Molokai, a total of 335 records, but not necessarily for that number of individual stations, there being in a number of cases several records of observation for one and the same place. An attempt has not been made to consolidate the several series just mentioned into a single consecutive series.

The object of this paper is to draw attention to the statistical data thus made available and to very briefly touch upon some of the best-known characteristics of Hawaiian rainfall.

The outstanding feature of the rainfall distribution in Hawaii is the very wide variation from one place to another separated from each other by only a few miles, also by the wide variation in the amounts for the same months in different years.

As much as 31.95 inches of rain have been registered as falling on a single day and 102.46 inches in a single month of 31 days, or an average of 3.30 inches on each day of the month. The annual amounts range from a maximum of 562.00 to a minimum of 2.46 inches on the island of Maui.

Mean monthly and annual rainfall, by islands.—Table 1 below gives the monthly and annual means for each of the four large islands of Hawaii, Kauai, Oahu, and Maui. The monthly means were computed from the records of 10 years or more in length on each of the several islands and were taken from the regular monthly publication *Climatological Data, Hawaiian Section, 1923*, by Thomas A. Blair.

The small number of stations on both Lanai and Molokai and their geographic distribution make it inadvisable to attempt to compile a mean for those islands.

TABLE 1.—Average monthly precipitation, Hawaiian group, by islands

Stations	January	February	March	April	May	June	July	August	September	October	November	December	Annual
Hawaii.....	9.15	8.65	10.58	11.03	8.26	5.87	8.18	10.11	7.42	6.25	10.90	10.29	106.69
Kauai.....	5.84	4.60	7.66	4.27	3.94	3.40	5.60	6.11	6.39	5.98	8.25	8.29	70.33
Maui.....	5.81	7.51	8.65	10.20	7.35	5.82	7.67	9.85	6.84	6.42	10.37	11.20	86.69
Oahu.....	6.01	5.97	6.31	5.59	4.12	3.44	3.48	4.05	4.65	3.93	6.32	7.87	61.74
Group mean.....	6.70	6.68	8.30	7.77	5.92	4.63	6.23	7.53	6.32	5.39	8.96	9.41	83.84
Adjusted 30-day mean	6.50	7.01	8.05	7.77	5.74	4.63	6.04	7.30	6.32	5.23	8.96	9.13	-----

¹ Summary of the Climatological Data for the United States, by Sections, Washington, 1922. In Figure 3 of this publication, the block with the title "Oahu (Mountains) Leeward" needs a word of explanation in view of the well-known decrease of rainfall on the leeward side of the mountains.

The author of the publication in an unpublished letter indicates that the block as above indicated refers exclusively to that part of the Ko-o-lau Range extending from its crest a few miles to windward. It is recalled that the average altitude of these mountains is not more than 2,000 feet, not high enough to block the passage of the northeast trades. The rain that falls immediately in lee of the crest should be considered in the nature of an oversplash from the rain that falls on the windward side.—Editor.

The monthly means of the above table are to be considered as provisional rather than definitive. In computing the monthly means regard has been had primarily to length and reliability of the record rather than to geographic position on the islands.

It is perhaps well known that the majority of rainfall stations on the islands are at low levels and on the windward side, whence it follows that the island mean will be increased when a majority of the stations thereon have a windward exposure. It is believed that the means of Table 1 for both Hawaii and Maui are too large by reason of the disparity between the number of rainfall stations on the respective windward and leeward exposures. In the case of Molokai but two records are available, one of which is on the windward coast, the other being in the interior at an elevation of 800 feet. The annual average at the first named is 67.03 and at the last 34.82 inches. Lanai has but a single reporting station, situated nearly in the middle of the island at an elevation of 1,780 feet. The annual average is 35.70 inches.

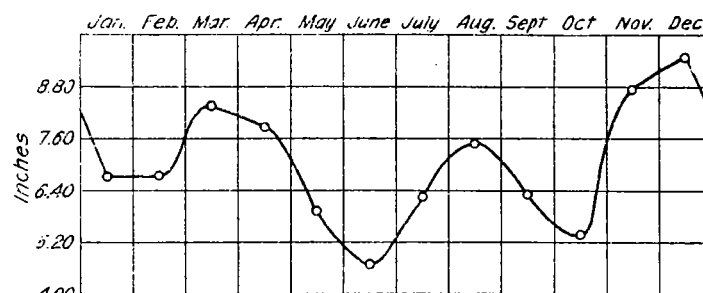


FIG. 1.—Composite curve of monthly rainfall distribution

Monthly distribution.—The group monthly means show three rather distinct maxima, one each in March, August, and December and three minima, one each in February, June, and October. Figure 1 presents these facts graphically. The chief maximum occurs in December and the chief minimum in October. These are most likely the more stable of the phenomena of monthly distribution. The August maximum is largely dependent upon the intensity and position of the North Pacific area of high pressure, which usually is centered about north latitude 40° and west longitude 145°; the spring maximum, which on Hawaii is deferred until April, is probably in some way related to the increased wind movement of that season coupled with the frequency of occurrence of southerly storms.

The chief minimum, which on Maui is deferred until October, comes in early summer at a time when cyclonic activity to the northward of the islands is at a low ebb and the pressure gradient for northeast winds is at the lowest point for the year. This minimum is most pronounced on Kauai and Oahu and on the leeward slopes of Maui, Molokai and in a much less degree in the Kau district of Hawaii.

The difference in latitude between the southern tip of Hawaii and the northern coast of Kauai is 3 degrees, a comparatively small distance when temperate latitudes are considered but probably too great to be disregarded in the Tropics. The February minimum is pronounced on the most northerly islands of the group, Kauai and Oahu, and is also in evidence on windward Hawaii, windward Oahu, windward Maui, and leeward Oahu.

Dr. B. M. Varney tells me that a weak secondary February minimum is noticeable in central and southern California rainfall. I have also found a decided minimum for a mountain station in Porto Rico, although the record is for but nine years' observations. The geographic situation of that island is somewhat analogous to the Hawaiian group, viz, in about the same latitude and southwest of a great oceanic area of high pressure, the Azores HIGH.

The autumn minimum in Hawaii comes at a season when the atmospheric processes that cause rain are inactive, and in this respect the conditions in the Hawaiian group are not materially different from those which obtain over continents.

The daily rainfall.—I have computed from the daily rainfall records of Hawaii, 44 stations in all, the average amount of precipitation for each day of January, 1923,

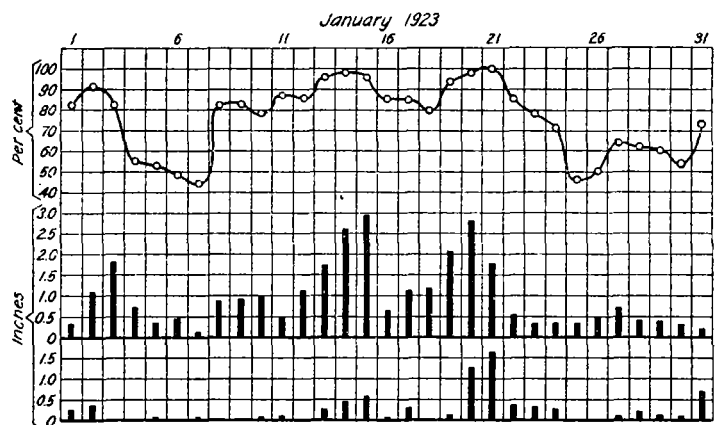


FIG. 2.—Percentage frequently of rainy days and average daily amounts of rain at 44 stations, island of Hawaii, during a wet month, January, 1923

a very wet month in the whole group; also the percentage of frequency. The latter was determined simply by counting the number of stations on which a measureable amount of rain was recorded for each day of the month. These percentages have been plotted to form the irregular line at the top of Figure 2 and the series of vertical bars immediately below represents the average amount of precipitation for each day of the month. The lower set of vertical bars represents the average amount of rain that was recorded at the five stations in the leeward districts of Hawaii—north Kona and south Kona, respectively.

The rainfall of these two districts on the leeward side of Hawaii is essentially different from that of similar sides on the remaining islands, the chief difference being that the maximum amounts for the year come in the months of May, July, and August, as will be shown later. (See fig. 4).

The above diagram shows that considering the island as a whole a measureable amount of rain fell on every day of the month; in the leeward districts, however, this was not the case. The diagram further shows that there were at least three periods of three to five days each with some rain at 90 per cent or more of the stations

and that the average amount on these days was several times greater than on the other days. The lower set of bars shows that in leeward districts there were relatively greater rains on the days of high frequency and amounts in all Hawaii.

The causes of rainfall in Hawaii.—In general the primary cause of rainfall in the Hawaiian group is the pressure distribution over the North Pacific that controls the direction and force of the winds. The northeast trades, which some one has said blow "persistently and monotonously" over nearly all parts of the group, are the immediate cause of the rainfall. These winds, as is well known, pass over a very considerable extent of water surface and for the most part must be rather highly charged with water vapor. Meeting the high cliffs and other obstructions that abound on the windward shores of the several islands, they are forced upward, their moisture is condensed by the cold of elevation and falls as rain. Thus the rainfall must be classed as almost wholly orographic.

Average pressure charts and the rainfall of Hawaii.—When considering average pressure charts a mental reservation about as follows should always be made: While average pressure charts are good to look at, they very rarely represent the real conditions which prevail on any single day, month, or year; hence when we speak of the North Pacific HIGH as a distinct entity which has form and movement we, to a certain extent, create a false impression. What we really wish to express is the thought that the pressure over the North Pacific, as elsewhere over the oceans, is constantly changing and never remains at the same level and in precisely the same formation for more than a day or two.

Heavy rains in Hawaii, particularly in the months November to April, are associated with changes both of geographic position and intensity, of this North Pacific area of high pressure or, for short, the North Pacific HIGH.

The average position of this pressure formation in February, according to Bartholomew's Atlas, is close to the intersection of the 140th meridian of west longitude with the 35th parallel of north latitude. This HIGH has a seasonal shift as follows: In the cold season it approaches and at times merges with the continental area of high pressure over the Canadian Northwest. As the warm season advances the center of the HIGH is found farther and farther west and north; thus in August and September, which months mark its greatest development, its center is approximately in west longitude 150° and north latitude 40°; it then begins to recede toward the North American Continent to again begin its annual cycle of movement. The level of the barometer in this HIGH is lowest, 30.10 inches, in October; it increases to 30.20 in November and continues at that level until the end of March, then rises to 30.30 and maintains that level, April to September, both inclusive.

As indicated in the above paragraph, the North Pacific HIGH is not so pronounced in the winter as in the summer; hence it follows that the trade winds of winter are less stable than in summer when the HIGH is best developed; moreover, the frequency and intensity of cyclonic systems that pass eastward along the Aleutians in winter is a second factor which tends to increase and at times reverse the direction of the prevailing winds of the Hawaiian Islands. Owing to the low latitude of the islands, very few, if any, fully developed cyclonic systems pass directly over them, and cyclonic rainfall, as such, rarely occurs. Nevertheless, in the months from November to April, the procession of cyclonic storms or areas of

low pressure is moving across the North Pacific from west to east in the neighborhood of the 52d parallel of north latitude or along the Aleutians. Each of these LOWs is attended by a fall in pressure, which on the average shades off from four-tenths to five-tenths of an inch at its center to, say, one-quarter of that amount in the region occupied by the North Pacific HIGH; thus pressure in the high suffers a reduction whenever a LOW moves east along the northern path. As the pressure is reduced the gradient for northeast winds over Hawaii is also diminished, and when the pressure reduction is great enough that gradient is replaced by one for SE. to S. or even SW. winds, which characterize the so-called "Kona" or southerly storms² that are a feature of the cooler season in the islands. Thus it results that those slopes which were leeward slopes during the prevalence of the trades now become windward slopes, and, like the former windward slopes for northeast winds, now receive generous rains.

The occurrence of one or more southerly storms in a single month will increase the rainfall of that month several fold as compared with a dry month. During the years 1905 to 1923, 38 months out of the 228, or 17 per cent, had a rainfall of 10 inches or more. The distribution of these months throughout the year was as

and increasing the rainfall. The fact that the wind has been southerly for a few days increases the likelihood of heavy falls of rain by reason of the presence over the islands of a mass of warm southerly air of high moisture content.

High pressure at Honolulu is associated with light rainfall and conversely low pressure with heavy rainfall, the explanation being that with high pressure there are few, if any, interruptions to the NE. trades, and conversely low pressure is indicative of frequent interruptions. A normal or weak trade is indicative of moderate rains on windward slopes and little or no rain on leeward slopes.

Notes on Hawaiian rainfall based on the Northern Hemisphere Weather Map.—This map for the last year or so has been prepared from radio reports of meteorological observations made on board ships navigating the Pacific. Together with reports from Honolulu and Midway Island it serves to illuminate the character of the pressure formations that control the weather of the islands, and especially the relation of the pressure distribution to heavy rains on the islands. I invite attention to the two groups of days January 12–15 and 19–21, 1923, as illustrated in Figure 2. The pressure distribution associated with these two groups was in the beginning

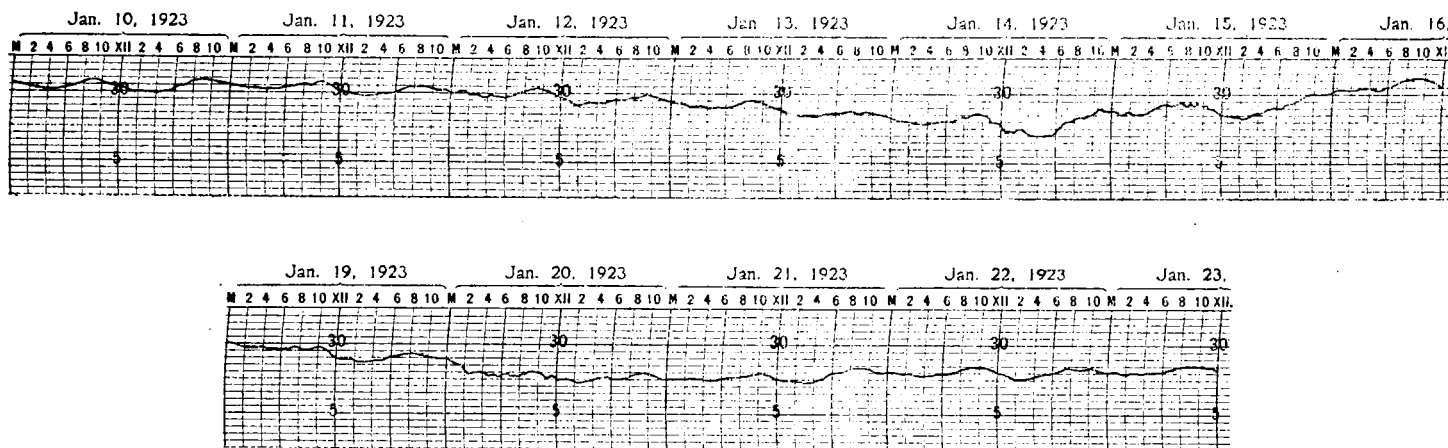


FIG. 3.—Barograph traces at Honolulu, January, 1923

follows: Winter, 18; spring, 11; summer, 3; and autumn, 6. June and October had no rainfall of as much as 10 inches. The months of heavy rains were irregularly distributed throughout the period, the first half having but 12 as against 26 in the last half. In the latter there were three consecutive years with rainfall above the average, 1921–1923. The islands have therefore just passed through a time of greater than the average rainfall. Casual inspection of the data does not indicate that any definite cycle in the rainfall is operative. Other studies, however, as indicated in the next paragraph, point to a different conclusion.

Mr. Joel B. Cox in his paper on "Periodic fluctuations of rainfall in Hawaii"³ postulates the existence of a 3.7-year period and submits the evidence therefor. He also finds evidence that cycles of 11.1 years and 33 years are present in Hawaiian rainfall.

Rising pressure is also an important factor in the rainfall regime of Hawaii. So soon as pressure begins to rise after a fall the winds become northerly and northeasterly, thus temporarily intensifying the NE. trades

one that gave a gradient for fresh northeast winds. This gradient weakened on the 13th and was considerably intensified on the 14th and 15th with maximum wind velocities at Honolulu of 56 and 55 m. p. h., respectively. This change in gradient was induced by changes in pressure of which the only example available is that for Honolulu. The barograph traces for that station for the periods in question are reproduced in Figure 3 above. Examining these closely it will be seen that the diurnal pressure variation so characteristic of the Tropics is in evidence throughout the period, but that it is considerably disturbed on several days. The 10 a. m. and 10 p. m. diurnal maximum is clearly shown in the traces for the 10th and the 11th, but on the 12th, while the 10 a. m. maximum is plainly shown, the p. m. minimum for that date is perceptibly lower than for the previous day; the immediately following maximum is also a shade lower than it was on the 12th. The fall thus initiated continued slowly and reached its lowest level on the p. m. of the 14th. Compare that minimum with the one of the 12th 48 hours earlier. This change is unlike those which occur in higher latitude on the approach of a barometric disturbance, being much slower in completing the change from high or normal to low and back

² Cf. Daingerfield, L. A., Kona Storms. MO. WEATHER REV., 49: 327–329. Blair, Thomas A., Trade Winds of Hawaii. MO. WEATHER REV., 51: 525, 526.
³ Transactions of American Soc. of C. E. 87:461 (1924).

to its initial level; the amplitude is also much less. The pressure did not again reach the level of 30 inches until 10 p. m. of the 15th; after remaining close to that level for several days it again began to fall on the 19th, and, as in the preceding case, the fall is first apparent in the 10 a. m. maximum of the 19th. The lowest level was reached on the 20th, but the barometer remained low throughout the remainder of the month, with variable winds and moderate rainfall. (See fig. 2, as to rainfall).

The cycle of changes described above is most likely due to a fall in pressure that advances from west to east in synchronism with the west-east movement of extratropical cyclones over the path which passes along the Aleutians or close to the parallel of 52° north latitude. It is probable that there is a slight southward seasonal shift in the latitude of North Pacific cyclone paths in the cold season and that on occasions these storms pass nearer to the Hawaiian group of islands than at others. Obviously the magnitude of pressure changes at Honolulu depends largely on the closeness of approach of the extratropical cyclones of the North Pacific.

The orientation of the longer axis of the North Pacific HIGH, whether west-east or north-south, is also an important factor in the weather control of the islands. If the longer axis takes a north-south or a northwest-southeast direction, southerly winds over the Hawaiian group and the resulting weather conditions will follow. The speed of movement of traveling areas of high pressure that advance from the Asiatic mainland across the North Pacific is also important; rapidly moving HIGHS will bring more frequent changes in wind direction and consequently in the weather, than slow moving ones.

Any sketch of the rainfall of the Hawaiian group would be incomplete without special reference to that of leeward Hawaii, or the north and south Kona districts, respectively.

These districts are in the shadow of the great mountain masses of Mauna Loa and Mauna Kea, whose summits rise far above the upper limit of the northeast trades. These latter therefore are not in any way an important factor in the rainfall of the Kona districts.

I have just come across an account of the summer showers of leeward Hawaii written some 40 years ago by the late Maj. Clarence Edward Dutton, Ordnance Corps, United States Army, who made a geological reconnaissance in the islands in the early eighties.⁴

Major Dutton says in connection with his observations on the weather of the islands:

I was much impressed with the fact that the trade wind is not felt on any of the high mountains above 7,000 to 8,000 feet. The upper part of this island [Mauna Loa] is in a region of comparative calm, excepting the uppermost 2,000 feet, where a gentle wind blows in a direction opposite to the trade wind.

His account of the weather of the Kona districts was evidently based on conversations with the inhabitants. It is summarized in the next paragraph.

In the morning the sky is clear and the sun shines gloriously; after sunrise the air is dead calm, but about 10 o'clock the sea breeze sets in, blowing from the west, and ascends the mountain slopes. Quickly the clouds gather, and at length rain falls steadily throughout the afternoon and into the night. At 9 or 10 o'clock the wind ceases and the land breeze sets in. As a rule there is no rain at the lowest levels upon the margin of the sea. There is a narrow belt of land close to the ocean ranging in width from a mile to a mile and a half or even 2 miles where rain seldom falls. Here the slope is comparatively

gentle and as the sea breeze blows inland the effect of the ascending current is not felt until the stronger slopes a couple of miles inland from the sea are encountered.

In the main this account faithfully describes the weather of Kona districts. A more recent statement is that supplied by Mr. Lawrence H. Daingerfield, who was in charge of the Hawaiian service from 1918 to 1922 and visited the Kona region in July 1922. In an unpublished letter to the editor Mr. Daingerfield says:

From personal observations when in Kona and especially when ascending Mount Hualalai, 8,269 feet, in north Kona, I can say that I saw that there occurs a distinct strengthening of the south-westerly wind in the day time which brings in the clouds (forced cumuli I called them) and frequent showers. At the same time the trades brought in clouds from the northeast, and I observed the "battle of the clouds" on Hualalai Summit, a wonderful although not unusual occurrence at that point.

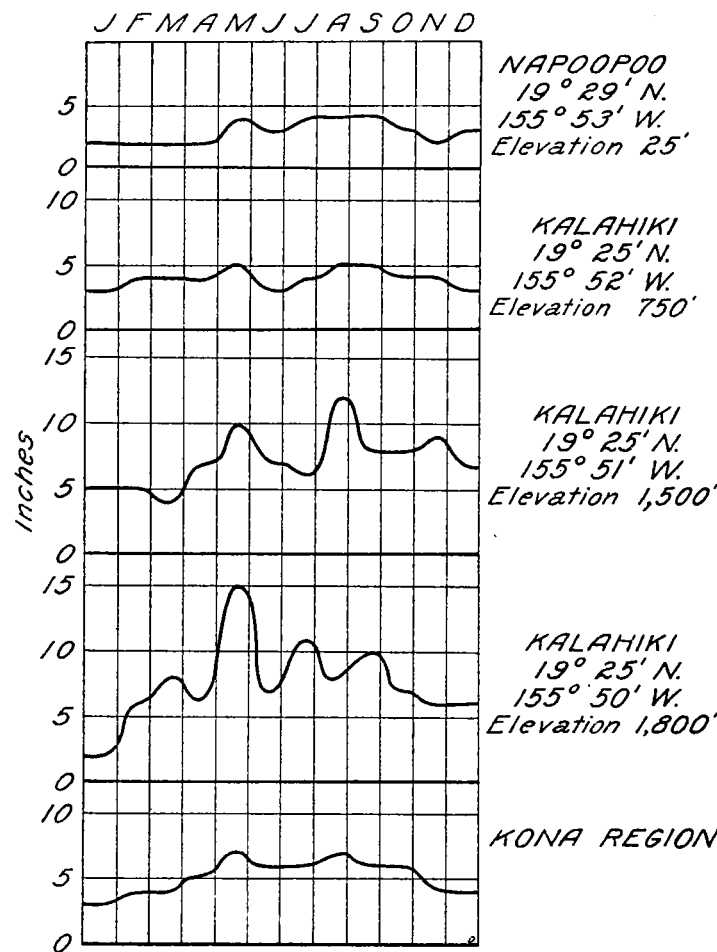


FIG. 4.—Monthly rainfall distribution in Kona districts of Hawaii

It has been definitely established that there is practically no wind in the Kona districts except the land and sea breezes, a condition that facilitates vertical convection in the daytime. The occurrence of thunderstorms in this region is also evidence of instability in the lower air levels. On the whole it is quite probable that vertical convection plays no unimportant part in the rainfall of the leeward districts of the Island of Hawaii.

In Figure 4 I present curves to illustrate the monthly rainfall distribution in south Kona. The top curve is that for Napoopoo, a station on the beach, as indicated by its geographical coordinates. Here there is a distinct increase in the rains of May with a diminished fall in June. The latter, however, is a month of minimum rain-

⁴ C. E. Dutton, Hawaiian Volcanoes. Annual report, Director of U. S. Geological Survey, 1883, pp. 81-219.

fall in most of Hawaii. The next three curves are presented to show the marked influence of altitude, beginning with the Kalahiki station at 750 feet and followed by two other records in the immediate neighborhood at altitudes of 1,500 and 1,800 feet, respectively; and finally the curve at the bottom is a composite one made from all the available rainfall records of both north and

south Kona. The bottom curve shows that the months of greatest rainfall coincide with the growing season of sugar cane in the Kona districts. These districts being in the shadow of the mountain masses of Mauna Kea and Mauna Loa are, as noted above, not subject to trade winds, and thus less moisture is lost by evaporation than in districts having a northeast exposure.

SOME OUTSTANDING AEROLOGICAL PROBLEMS

By WILLIS RAY GREGG

[Presented before the American Meteorological Society as a part of the "Meisinger Memorial," January 3, 1925, Washington]

It is a very good thing to pause occasionally in our work, take stock of what we are doing and endeavor to determine what new lines should be taken up and what changes, if any, in the old should be made. It is, I think, peculiarly fitting that we do this now when we are considering the work of Doctor Meisinger, for he was, to a greater degree than any one else I have known, absorbed with the fascination of ferreting out the secrets of the atmosphere. Less than a week before he left for his work at Scott Field we talked for an hour of the problems that lie before us, some of which he planned to attack upon his return, and in all of which he was ready and eager to give his assistance and advice. And so this brief talk constitutes, in a sense, a recapitulation of what we discussed at that time. I shall be glad indeed if it leads some aspiring student, by a contribution along one or more of the lines suggested, to earn an award under the Meisinger Aerological Research Fund, concerning the purposes and present status of which you are shortly to hear.

The problems I shall name (I can do little more than name them, in the time allotted) are not given in any order of relative importance, except that the last one is, to my mind, the most important.

1. *The diurnal variation of meteorological elements at different heights.*—This is, perhaps, a subject of greater theoretical interest than of practical value, although it may be pointed out that the diurnal variation in wind speed at moderate heights plays an important part in determining regular flight schedules. We know that the phase characteristic of the surface, viz, maximum velocity in the afternoon, minimum in the early morning, is reversed above 100 meters; that, between about 300 and 1,000 meters the diurnal amplitude is large, amounting to 3 or 4 m. p. s., on the average; and that, above about 1,500 meters there is essentially no variation.

Studies of the temperature variation agree in showing a diminishing amplitude from the surface to about 1 to 2 kilometers, where it is very small, less than 1° C., but these studies give contradictory results at greater heights. Some investigators claim a reversal of phase in these upper levels. More recent and more abundant data at Drexel and other stations in this country, however, indicate that the phase is essentially like that at the surface and that the amplitude is about 1° C. These later data represent practically all varieties of weather conditions, and the same results are shown for all parts of the year. The investigation is, however, in a preliminary stage only. It should be pushed to completion, and extended to the other meteorological elements, such as humidity, pressure, density, wind, etc. The data we now have, as the result of numerous series of successive kite flights covering periods of 24 to 30 hours, are ample for a complete and authoritative analysis of this problem.

2. *Winds and weather along airways.*—This is a problem of immediate practical value. In order intelligently to determine regular flight schedules for commercial or

other purposes it is essential to know, for different sections of an airway, the resultant wind at flying levels, the percentage frequency of wind speeds above certain limiting values and the percentage frequency of occurrence of weather conditions, such as widespread heavy precipitation, blizzards, etc., that make flying impossible or at least hazardous. Studies along this line have already been completed for Oklahoma and east Texas and for the New York-Chicago airway. They should be extended to all sections of the country where regular flying, commercial or otherwise, is likely to develop, and preferably this should be done before such development takes place. For much of the eastern and central portions of the country suitable data for this problem are now available.

3. *The free-air in thunderstorms.*—Thunderstorms constitute the most difficult condition of the atmosphere to explore. For man-carrying aircraft to attempt this is suicidal; pilot balloons quickly disappear in the clouds, and even while in sight yield data of doubtful value, owing to vertical air movements, unless observed with two theodolites; and kite flying frequently results in destruction of the kite line and damage to the equipment, besides involving the possibility of injury to personnel. Nevertheless, a considerable mass of data has been collected, mostly perhaps immediately before and after the thunderstorms, but partly also within them. It is believed that an analysis of the data in hand would be fruitful, and would admirably supplement some recent statistical studies.

4. *Clouds.*—Notable contributions to this subject have been made in the past 30 years or so, and much of our knowledge of the larger features of the planetary circulation are based upon these studies. The field is far from exhausted, however. Little is known, for example, as to the average and extreme thickness of the different types, the variations in height, thickness and speed with latitude, in different parts of cyclones and anticyclones and in elevated as compared with low-lying regions. We need to know more than we do now with reference to lapse rates in clouds and their relation to precipitation. Data for these studies, although perhaps not adequate for a final settlement of them, are nevertheless quite abundant, through the observations we have made with kites and pilot balloons, and would, it is believed, well repay earnest effort on the part of those who can undertake their analysis. These data should of course be considered and combined with the results of earlier investigations, such as those of the International Cloud Years. The latter yielded information of immense value. It seems certain that the more recent data will supplement those where they were weak and bring the whole subject to a more satisfactory status than has heretofore been possible.

5. *The free air in the Tropics.*—The planetary circulation more closely approaches its ideal state in this region than in any other. It is here comparatively free from